Free-Form, High Energy Performance, Transparent Vacuum Envelope

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Abstract.
This article examines a new lightweight, slim, high energy efficient, light-transmitting, self-supporting envelope system, providing for seamless, free-form designs for use in architectural projects. The system exploits vacuum insulation panel technology. The research was based on envelope components already existing on the market and patents and prototypes built by independent laboratories, especially components implemented with silica gel insulation, as this is the most effective transparent thermal insulation there is today. The tests run on these materials revealed that there is not one that has all the features required of the new envelope model, although some do have properties that could be exploited to generate this envelope, namely, the vacuum chamber of vacuum insulation panels, the use of monolithic aerogel as insulation in some prototypes, and reinforced polyester barriers. These three design components have been combined and tested to design a new, variable geometry, energy-saving envelope system that also solves many of the problems that other studies ascribe to the use of vacuum insulation panels.

1. Introduction

Energy efficiency is coming to the forefront in the architecture, as, apart from the significance of a reduced environmental impact and increased comfort for users, the current energy crisis and economic recession has bumped up the importance of the financial cost of energy.

Since the Kyoto Protocol was signed in 1997, governments all over the world have been trying to reduce part of the CO_2 emissions by tackling building "energy inefficiency". In Europe today, the tertiary and housing sectors account for 40.7% of the energy demand, and from 52 to 57% of this energy is spent on interior heating [1]. The new world energy regulations, set out at the European level by the Commission of the

European Communities in the First Assessment of National Energy Efficiency Action Plans as required by Directive 2006/32/EC on Energy End-Use Efficiency and Energy Services, [2] indirectly promote an increase in the thickness of outer walls, which, for centuries, have been the only way of properly insulating a building.

The use of vacuum insulation panel (VIP) systems in building aims to minimize the thickness of the building's outer skin while optimizing energy performance. The three types of vacuum chamber insulation systems (VIS) most commonly used in the construction industry today –metallized polymer multilayer film (MLF) or aluminium laminated film, double glazing and stainless steel sheet or plate [3]–, have weaknesses, such as the fragility of the outside protective skin, condensation inside the chamber, thermal bridges at the panel joints, and high cost, all of which have a bearing on on-site construction [4].

Apart from overcoming these weaknesses and being a transparent system, the new F^2TE^3 (free-form, transparent, energy efficient envelope) system that we propose has two added values. The first is the possibility of generating a *structural skin* or *self-supporting* façade. The second is the possibility of designing free-form architectural skins. These are research lines that the Pritzker Architecture Prize winners Zaha Hadid, Frank Gehry, Rem Koolhaas, Herzog & de Meuron, among many other renowned architects, are now exploring and implementing.

To determine the feasibility of the new envelope system that we propose, we compiled, studied and ran laboratory tests on the materials and information provided by commercial brands. We compared this information to other independent research and scientific trials on VIPs, such as Annex39 [5], and on improved core materials, such as hybrid aerogels and organically modified silica aerogels [6], conducted by independent laboratories like Zae Bayern in Germany [7], the Lawrence Berkley Laboratory at the University of California [8] or the Technical University of Denmark [9].

After studying the results, we discovered valuable innovative ideas that we exploited to design the new high energy efficient envelope that should outperform the elements now on the market.

The remainder of the article is structured as follows. In Section 2 we explain the rationale of the epistemological study of the system, and how the experimental study combining computer simulations and empirical trials was run. In Section 3, we describe the design of the proposed envelope system (F^2TE^3), explaining the solutions adopted in this new system and the improvements on other existing systems. Section 4 analyses how the F²TE³ system overcomes the weaknesses detected in existing VIP systems. Finally, Section 5 discusses final conclusions.

2. Research

2.1 Epistemological study of the system

Today both vanguard architecture and the conventional building industry are demanding a constructive system such as is proposed in this research: a lightweight and slim, free-form and seamless, high energy performance system, which facilitates the passage of natural light and natural backlighting and can be used to design self-supporting structures.

After a comparative study of over 147 commercial products and industrial prototypes with each other and against data gathered from studies and independent laboratories, we determined that no system combining all these features exists as yet. Similar systems are not absolutely free form or translucent, are not seamless and/or have a very limited thermal response, among other weaknesses already listed above. The proposed system overcomes these flaws.

2.2 Experimental study

We compared the results of the epistemological study with the findings of empirical experiments and computer simulations run on commercial panels and prototypes to which we had access.

2.2.1 Computer simulation

Because of the shortage of information about aerogel and the impossibility of acquiring a sample, we used the DesignBuilder program to conduct a trial by computer simulation under the same environmental conditions as the empirical trials (see Figure 1).

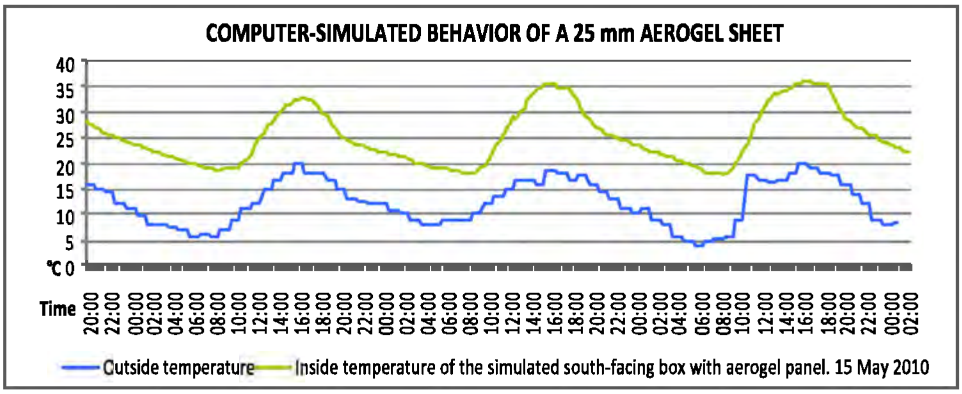

Figure 1 Computer simulation for a 25mm thick sheet of silica aerogel with density 50-150kg/m³ over 78 hours.

3.2.2 Empirical trials

We ran trials to measure the energy performance of the material. These trials were run at the UPM [10] School of Architecture's Department of Building and Architectural Technology using boxes with an inner volume of 60x60x60cm, insulated with 20cm of expanded polyurethane. One of the box faces was left open by way of a window. The study elements were placed in this opening using a specially insulated frame. The trial involved exposing two such boxes to a real outside environment to study their behaviour. The two boxes had two different windows: one was fitted with 6+8+6 double glazing with known properties as a contrast element and the other was fitted with the panel that we intended to study. Data-loggers were placed inside each box for monitoring purposes. There was a thermal sensor on the outside to capture the temperature to which boxes were exposed. The boxes were set in a south-facing position as this is the sunniest exposure (Figure 2).

Figure 1 Energy performance testing of the UPM system based on the hot box method

We ran 28 temperature-measuring trials using this system, and compared the performance of different thicknesses of commercial panels with 6+8+6 double glazing. Of these trials, the four panels that best combined high light transmittance with a good energy efficiency level were evaluated against the data of the computer-simulated aerogel trial (see Figure 3).

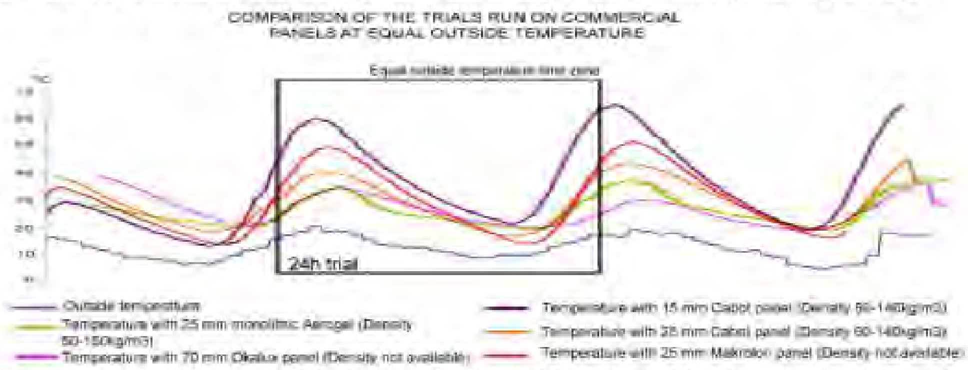

Figure 3 Comparison of empirical data of commercial systems with computer simulation of 25 mm thick sheet of silica aerogel with density 50-150kg/m³ over 78 hours (temperatures inside the test boxes)

This research confirms that vacuum chamber panels perform better than the other tested systems. It also reveals that, by combining some features of existing elements, such as the vacuum chamber, a core of monolithic aerogel, sandwiched between glass fibre barriers, an innovative system can be designed. This system offers a new free-form, seamless, self-supporting, slim, transparent, high energy efficient VIP envelope, thereby improving on the properties of the VIP panels now on the market.

3. Proposal for a Free-Form Transparent Energy Efficient Envelope (F^2TE^3)

We propose a free-form design envelope system fabricated with cellulose fibres and polyester resin (or acrylic-based organic resin), and a vacuum core insulated with monolithic aerogel at a pressure of 1hPa. Being a self-supporting component, the system can perform structural functions, and seams between panels are concealed by an outer coating applied in situ (Figure 4)

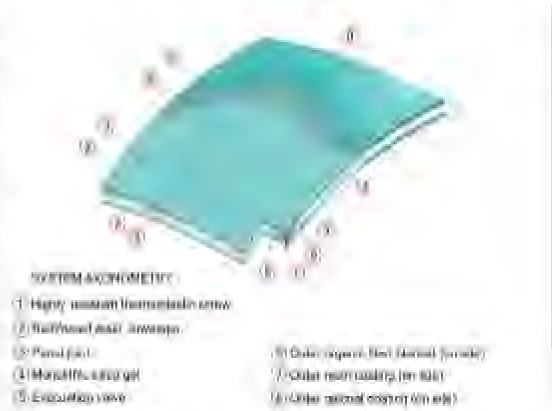

Figure 4 F^2TE^3 system axonometry

F^2TE^3 dimensions: The minimum thickness of the modelled system panels will be 25 mm, and the sheet width, although variable, will be at most 600x600 mm. The weight per unit area will range from 15 to 7 kg/m2, and the minimum admissible flexion radius will be approximately 4000 mm. Other features are:

- Light transmittance, τD65: from 59% to 85% approx.
- UV absorption: approx. 20%
- Total energy: approx. 61%
- Horizontal and vertical U-value: 0.50 W/m2 K
- Thermal conductivity coefficient: α 0.065 mm/m °C, estimated
- Possible heat-and humidity-induced dilation: 3 mm/m approx.
- Maximum temperature: should withstand temperatures of from 120°C to 250°C
- Weighted sound reduction value: estimated at 26-45 dB
- Impact resistance: should be within the EN 356-P5A limit
- Fire resistance: European (EN13501) resistance regulations compliant

System assembly: The F^2TE^3 system is composed of the dry-seal connection of male and female edged panels (two female sides and two male sides on each panel that fit together seamlessly) as previously designed by the draughtsperson. Once the construction is in place, it is given an outer coating of fibres and resins and finally a gelcoat coating to protect the assembly from external agents.

Testing: A 25 mm thick prototype F^2TE^3 system was computer simulated to examine its energy-saving behaviour compared with a computer-simulated aerogel envelope of the same thickness (Figure 5)

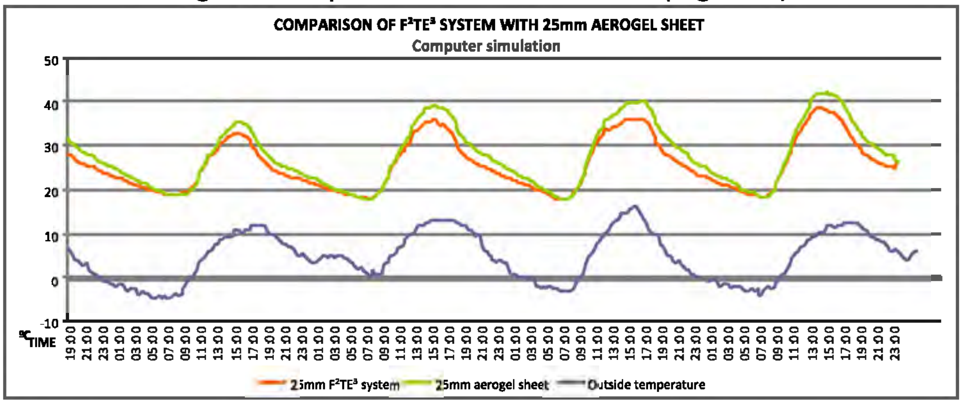

Figure 5 Comparison of a computer simulation of a 25mm thick sheet of silica aerogel with a density of 50-150 kg/m³ with the F^2TE^3 system over 96 hours.

As shown in Figure 5, the F^2TE^3 returns a better result than what would be achieved with monolithic aerogel without a barrier envelope (not feasible due to aerogel hydroscopy). The flat heat loss curve indicates that the U-value is very small and eventually equals the values for aerogel, whereas F^2TE^3 has a 5ºC edge over aerogel for capture.

4. F^2TE^3 response to the weaknesses of VIP systems

Most studies conducted in the field of VIP elements (VIS) [11] determine that there are four key obstacles to the use of these systems in the building industry: a) fragility of the outer skin, b) thermal bridging at panel edges and joints, c) vacuum chamber condensation, and d) price. On top of these weaknesses, there is the added obstacle of a single element having to provide both transparency and energy efficiency, plus a new demand from vanguard architecture for generating free forms by means of monocoque systems.

Theoretically, the new F^2TE^3 overcomes all the above objections raised against VIPs, offering the added values of transparency and free-form design:

a) Fragility of the outer skin: As the new system has to be a transparent and self-supporting structure, we have replaced the fragile outer barrier elements, such as a metallized polymer multilayer outer skin, double glazing and thin stainless steel sheets, with an element composed of highly resistant reinforced fibre resin.

b) Thermal bridge at panel edges and joints: Commercial panels are not designed to be assembled to form seamless elements. The new system that we propose is purposely designed to generate monocoque elements through a system of male and female panels. This system eliminates the thermal bridge between the panels (see Figure 6).

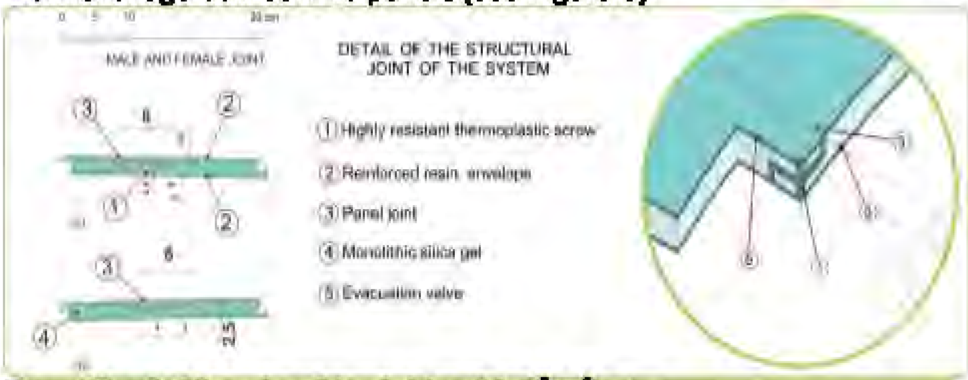

Figure 6 Detail of the male and female joint of the F^3TE^3 system.

c) Condensation in the vacuum chamber: One of the key problems of VIP systems is condensation forming inside the chamber. Although some studies estimate that the hydroscopic silica smoke is capable of absorbing most of the minimal amount of condensation that forms without compromising its load-bearing or thermal capacities, the fact is that humidity inside the chamber ends up turning the monolithic aerogel opaque.

F^3TE^3 solves this problem by modifying the barrier thickness. The outside face is 3 mm thick compared with the inside face that should have thicknesses ranging from at least 6 to 8 mm to prevent condensation forming inside the chamber. We used the COAG's memories2 program to plot the condensation graph of the new envelope, and the resulting sections are shown in Figure 7.

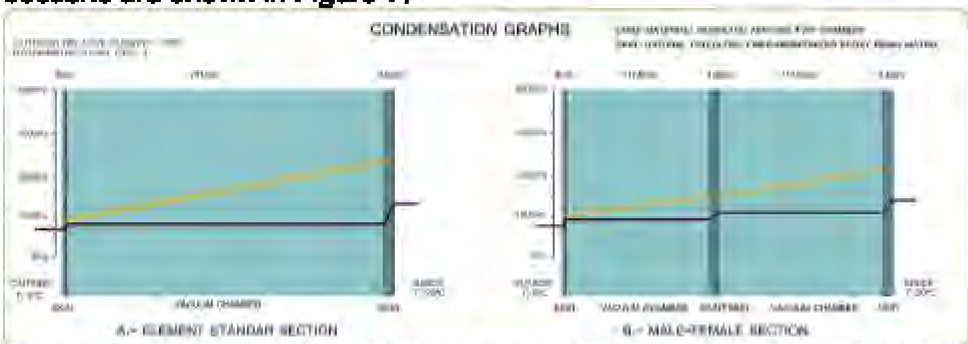

Figure 7 Condensation graphs for a standard section and a male female section of the new F^3TE^3 system.

d) Price: VIP systems are now much higher cost than traditional building systems (approximately 1,000 €/m²). However, Technical University of Denmark (DTU) studies [9] show that the mass produced product, using a fully automatic 10m³ autoclave (as the sol-gel process is the most expensive part of the fabrication of this system), could be commercialized for on-site delivery at 277 €/m².

For the purposes of our calculations, we will take a 150m² detached dwelling and assume that the F²TE³ system costs 300 €/m². On the other hand, the mean cost of a 6-12-6 double glazing aluminium window with a thermal break is 360 €/m², whereas a plastered, double hollow brick lined, 4 cm thermally insulated, 6 inch rough brick conventional wall with single-layer finish costs on average 85.40 €/m². Assuming that the mean percentage of glazing is 45%, the current cost of a conventional envelope including the façade glazing is 162 €/m².

The surface area of the envelope for a 150 m² dwelling is 375 m². The cost of building a conventional wall will be 60,750 €, whereas F²TE³ costs 112,500 €, meaning that F²TE³ costs just over double the traditional system at this stage.

Note, however, that the net internal area of the dwelling built using the F²TE³ system is 148.75 m² (at 2.5 cm thick the envelope only takes up 0.833% of the gross external area), compared with 135.36 m² for the traditional system (at 30cm thick it takes up 9.7% of the gross external area). Therefore, developers using the new F²TE³ system can commercialize an additional net internal area of 13.39 m². Assuming that the final sale price per square metre of net internal area is 4,000 €, there will an additional gain of 53,560 €. This, deducted from 51,750 €, which is the result of subtracting the price of the conventional building skin from the cost of the proposed envelope, results in a net profit of 1,810 € for developers using F²TE³.

Clearly, this calculation does not take into account either the potential saving thanks to the use of the new system as a structural element (which could amount to a 20% saving over the total cost of executing the building works) or the potential time and labour saving using this new building system compared with the traditional envelope.

According to DIN standard 4701, "there would be an annual saving of from 0.9-1.3 l of oil or 1.0-1.5 m³ of gas per m² of naturally lit surface area, leading to U-value reductions of 0.1 W/m²K". The F²TE³ surface area would be the sum of the walled areas (168.75 m²) and glazed areas (206.25m²). Accordingly, with a U-value of 0.35 W/m²K, compared with 0.44 W/m²K for the conventional wall and 1.2 W/m²K for the glazing, the proposed system achieves a saving of 2083.18 l of oil (0.7€/l) and 2403,67

m^3 of gas (0,55€/ m^3). This is equivalent to an annual saving of 1458.22€ in oil or 1322,02€ in gas for the consumer and a CO_2 reduction of approximately 4.9 kg per year.

Transparency, energy performance and variable geometry: Of the three types of translucent and transparent insulation now on the market (plastic fibres, gas and aerogel), we found that the best core material for the new F^2TE^3 system is aerogel, [12] [13] as it offers:

a) *Transparency:* aerogel compares with glass in transparency (87.6%)
b) *Insulation:* aerogel is an excellent insulator. According to published data, the thermal performance of a 70 mm nanogel-filled VIP panel is better than a 270 mm cavity filled wall
c) *Core material:* thanks to its porosity and friction joint sealing, silica smoke is the material that many studies [14] recommend as VIP core material, provided that there is an outer protective skin
d) *Lightness:* aerogel is only three times heavier than air [15]
e) *Versatility:* monolithic aerogel can be shaped as required [16].

5. Conclusions

F^2TE^3 is a slim façade system that provides high energy efficiency. It has a seamless surface, providing for variable geometry and the option of building self-supporting structures into the same transparent system skin. The study conducted as part of this research has shown that the prototype F^2TE^3 system outperforms other systems existing on the market, offering added value in terms of structure, transparency and variable geometry, and overcoming the traditional weaknesses of VIPs.

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